## 4.2. What is the optimum temporal/spatial resolution?

The use of a constellation of CubeSats for the study of deep convective clouds (Reising et al., 2018; Stephens et al., 2020) should be further explored through model simulations in a future ESA funded activity. Here, we will list the different considerations that could be include in such study using limited forward simulations of convective clouds. Two different cloud resolving numerical models are used in this study: The System for Atmospheric Modeling (SAM, Khairoutdinov and Randall, 2003) and the Regional Mesoscale Atmospheric Model (RAMS, Storer and Posselt, 2019). The SAM simulations have a 50 m horizontal and vertical resolution and the RAMS simulations have a 250 m horizontal resolution and variable vertical resolution (50 to 500 m). The numerical model output is available at variable time intervals from 30 sec, 5 min and 10 min in an attempt to capture different phases of the lifecycle of deep convective clouds. A vertical cross section from the RAMS model is shown in Fig. 15.

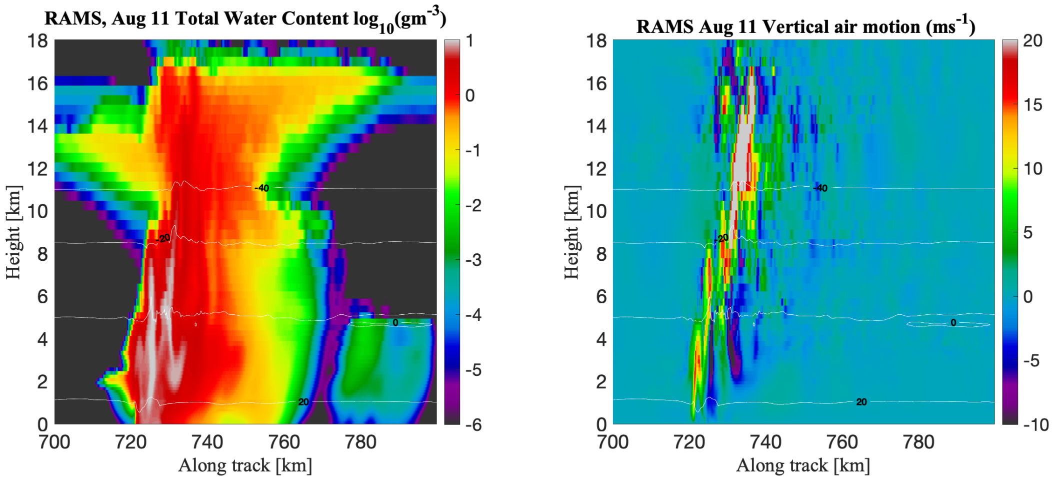



**Fig. 15: The total water content in gm$^{-3}$ and the corresponding vertical air motion in ms$^{-1}$**

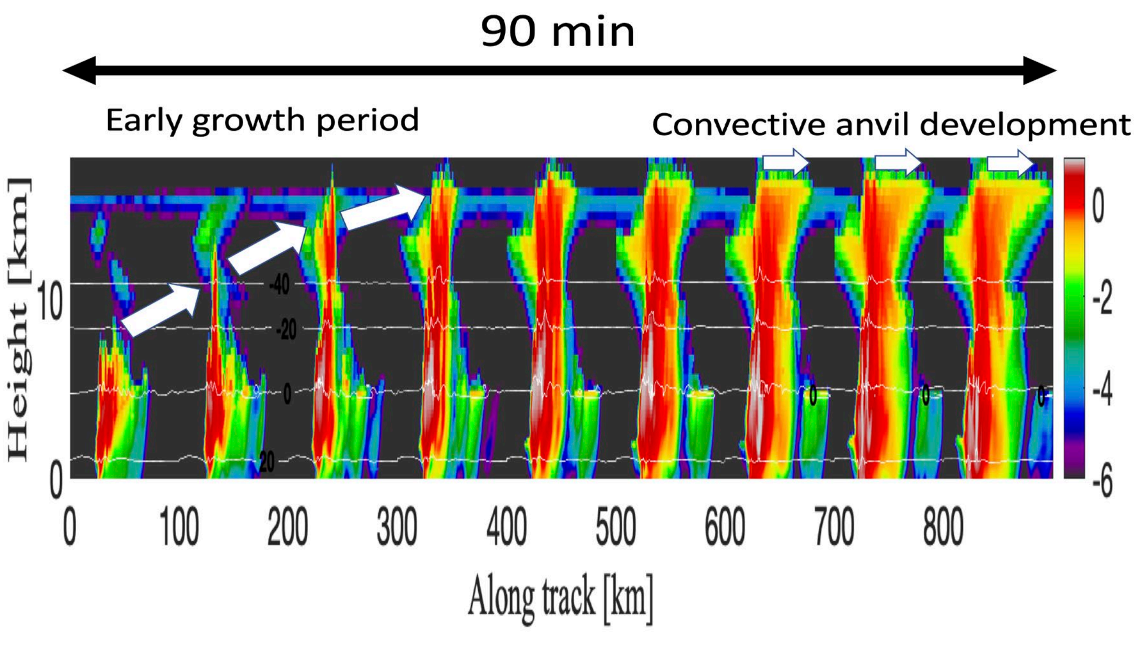



**Fig. 16: The lifecycle of a long-lived squall line simulation using the RAMS mode. Model output is available every 10 minutes.**

The selected RAMS/SAM simulations (Fig. 15) feature intense convection with very high amounts of water content and significant vertical air motion (magnitude between 10-20 ms$^{-1}$). In Fig. 16, a vertical cross section of a long-lived squall line simulation performed using the RAMS model is shown. The cross section as spaced by 10 min, thus, a 90 min is covered in Fig. 16. Several noticeable morphological features of the deep convective system are clearly visible in its vertical cross-section. During the early growth period, the deep convective cloud exhibit significant vertical growth, something that can observed using delta-t measurements of the radar cloud top height or using IR measurements from a Geostationary Satellite. During the mature stage, the most noticeable feature is the development of the convective anvil. Since these morphological features are space by 10 min apart, this suggest the use of a CubeSat constellation with significant temporal spacing, much longer than this suggested by Stephens et al., 2019 (D-train). In this time scale (10-30 min) it is highly unlikely that the deep convective cloud did not advect horizontally off the narrow along-track view of a nadir pointing spaceborne radar. This is clearly illustrated in Fig. 17 that shows horizontal cut of the same convective cloud at a height of 7.35 km. The vertical cross section shown in Fig. 16 is taken along the horizontal dashed line at 0 km cross-track. The thick diagonal arrow shows the location in along-track and cross-track coordinates of the maximum updraft velocity at the same level. It is clear that a nadir-pointing radar with no cross-track beam scanning capability (as suggested by the white circles) will mis-present the lifecycle of the deep convective cloud.

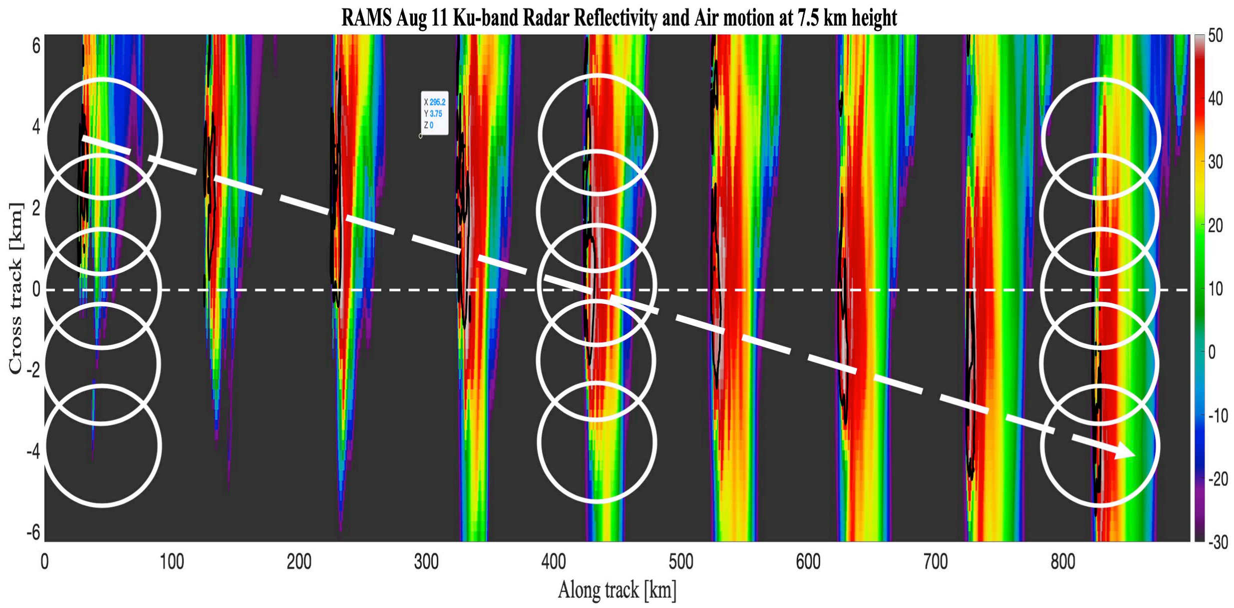



**Fig. 17: A horizontal cross-section of the RAMS simulation shown in Fig. 16 at an altitude of 7.35 km above sea level. The color bar shows the attenuated Ku-band radar reflectivity factor and the black contour corresponds to a 10 ms$^{-1}$ upward vertical air motion. The white circles indicate a 5-cross-track beam approach (feasible for a CubeSat) that would address the issue of horizontal advection and thus improve our ability to capture the lifecycle of deep convection.**

What about shorter time scales i.e. 30-90 sec as suggested in Stephens et al., for updraft mass flux estimates? Fig. 18 shows a vertical cross section from very intense GATE convection. The model output is available every 20 sec, thus, the entire cross section corresponds to 5-min obsevations. The total water content plot indicates very small changes in the overall storm morphology. However, the vertical air motion (albeit difficult to see in this graphical representation) does show considerable upward shift of the updraft cores (Fig. 18). Initially, there are two convective updrafts in the middle and upper levels of the storm and eventually a third one develops while the first one dissipates. Thus, when comes to Doppler velocities, there is considerable variability at small time scales (Oue et al., 2019).

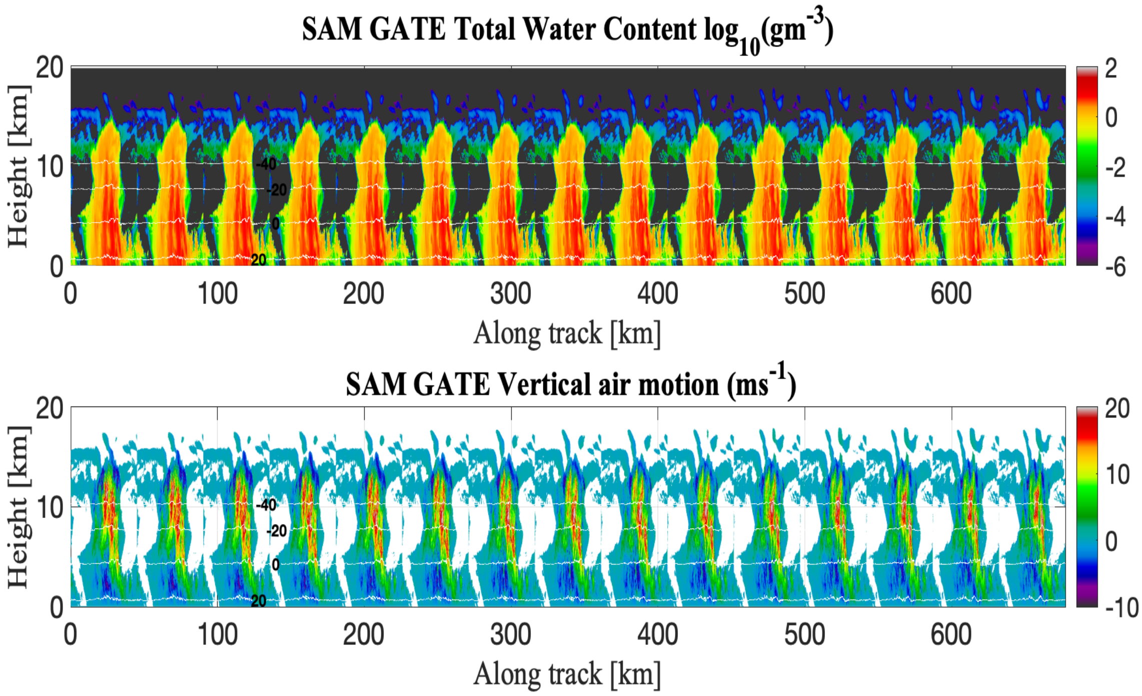



**Fig. 18: A 5-min evolution of a strong oceanic convective cell simulated using the SAM model and forcing from the GATE field campaign. Model output is available every 20 sec.**

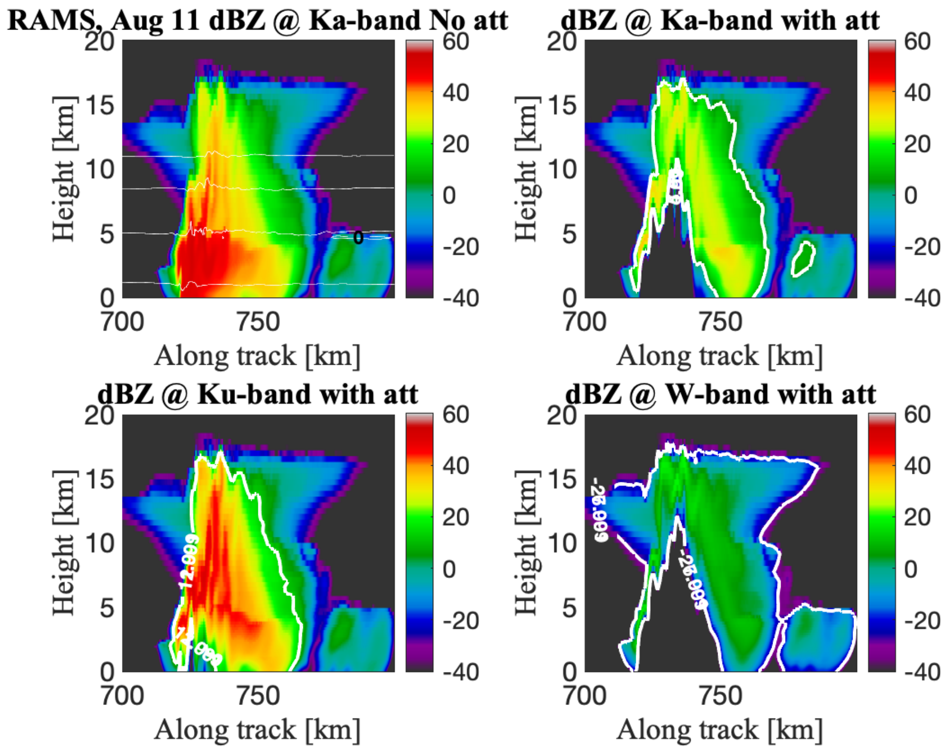
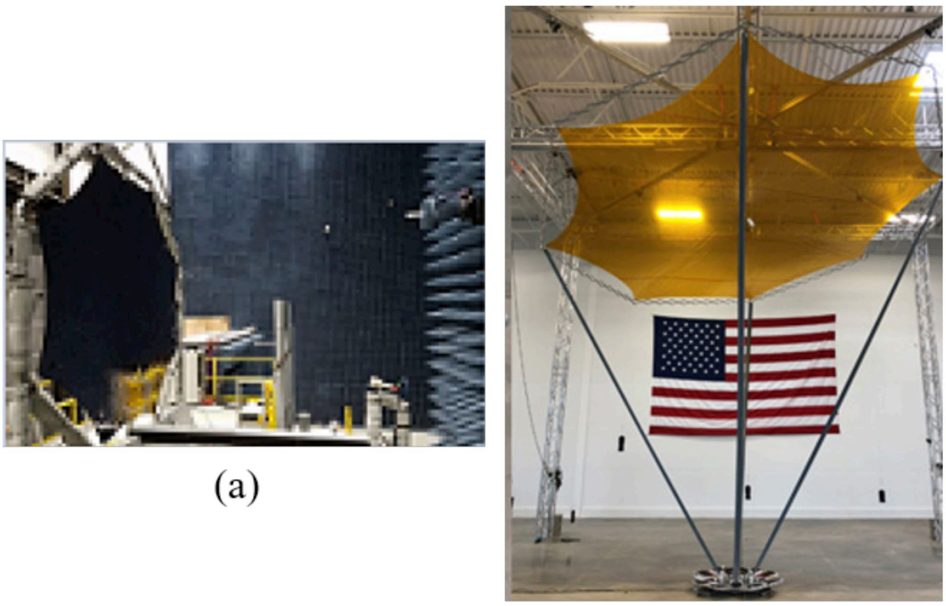



**Fig 19: A view of the same convective cell using three different CubeSats with different radar sensitivity. The top right panel is the model output in unattenuated Ku-band radar reflectivity, and the other three panels indicate the attenuated radar reflectivity at Ku-, Ka- and W-band. The white line indicates the expected sensitivity of these radars: +13, +7 and -26 dBZ, respectively.**

## 5. DOPPLER FROM CUBESATs AND SMALLSATs

In section 3, three different techniques for estimating vertical air motion in deep convective clouds using spaceborne radars were discussed. Here, we will discuss the potential to use these techniques in CubeSats and SmallSats. SmallSats are spacecrafts with a mass less than 180 kilograms and about the size of a large kitchen fridge and CubeSats are a class of nanosatellites (1-10 kilograms) that use a standard size and form factor. The standard CubeSat size uses a "one unit" or "1U" measuring 10x10x10 cms and is extendable to larger sizes; 1.5, 2, 3, 6, and even 12U.

Here, we discuss the advantages and disadvantages for Doppler velocity measurements in CubeSats and SmallSats using either a single antenna system (the EarthCARE CPR approach) or the DPCA technique that uses two antennas. The use of a large aperture antenna on CubeSats and SmallSats suggests the use of a deployable antenna (Fig. 20). Such technologies have better penetration at low radar frequencies. Fig. 20 shows large aperture deployable antennas at X-band. An effort to develop a Ku-band precipitation radar-based using this technology with a 5 m$^2$ aperture that could be accommodated on a SmallSat spacecraft are undergoing (Cooley et al., 2019). At higher radar frequencies (Ka-band), RainCube has demonstrate a 0.5 m deployable antenna and recently JPL demonstrated high TRL in 2.0 m deployable antenna for both Ka-band and W-band. However, the W-band deployable antenna has poor efficiency for Doppler measurements. Furthermore, as part of the NASA ACCP study, NASA is considering a MicroSat (10-100 kilograms) with on solid Cassegrain reflector and one offset-fed deployable antenna (both 1.6 m diameter) that will allow the use of the DPCA technique for Doppler velocity estimation at Ka-band and at the same time will allow radar reflectivity measurements at W-band. In addition, NASA is also considering a 2.1 m antenna size for the same MicroSat.



(a) (b)

**Figure 20. (a) 4 square meter X-band deployable reflect array in near field range testing. (b) Larger 14 square meter reflectarray engineering prototype undergoing stowage and deployment testing in high bay (Adapted by Cooley et al., 2019).**

*What is the significance of these technological developments?* That suitable antenna sizes at X-, Ku- and Ka-band are available in SmallSats and MicroSats for spaceborne Doppler velocity measurements. The antenna size is a very important parameter because it dictates the instantaneous field of view of the radar on Earth's surface. However, there are additional factors that need to consider when designing a spaceborne Doppler radar, especially on a Small/Micro Sat.

The Doppler performance for single antenna Doppler radar:

- Depends on how fast we transmit pulses (PRF)
  - High duty cycle, high orbit average power (300 W or higher)
- Depends on antenna size
  - Limited by spacecraft size and payload
- Depends on how well we can quantify NUBF
  - Depends on footprint and along-track oversampling
- Available only at high Signal-to-Noise conditions
  - Doppler available +6 dB above the single shot sensitivity
- Requires considerable Doppler post-processing
  - Aliasing, NUBF, denoising techniques

On the other hand, the Doppler performance for a DPCA radar:

- Does not depend on how fast you transmit pulses (PRF)
  - Low duty cycle, low orbit average power (~ 60W)
- Does not depend on antenna size
  - However, requires two antennas
- Does not depend on NUBF
  - Zero apparent Doppler velocity
- Available at low SNR conditions
  - Doppler is available 6 dB below single shot sensitivity
- Simplified Doppler post-processing
  - Easy to unfold Doppler, no NUBF, no de-noising techniques

It is apparent that a single antenna Doppler system requires much higher orbit average power level. In addition to the substantial differences in power requirements, Table 2 provides the Doppler velocity error budget for two Ku-band radar: one with a large aperture antenna (4 x 2 m) and another one with a two 2 x 2 antennas (DPCA).

| Ku-band Radar | Doppler broadening ($ms^{-1}$) | Non-Uniform Beam Filling ($ms^{-1}$) | Doppler velocity error ($ms^{-1}$) | Vertical air motion error ($ms^{-1}$) | Total vertical air motion error ($ms^{-1}$) | Sampling Bias ($ms^{-1}$) |
|---|---|---|---|---|---|---|
| Single antenna (4x2 m) | 2 | 2 | 2.8-3.0 | 2.0 | 3.4-3.6 | TBD (2.5 x 5.0 km) |
| Dual antenna (2x2 m) | 0.1-0.25 | 0.1-0.25 | 0.2-0.4 | 2.0 | ≈ 2.0 | TBD (5.0 x 5.0 km) |

The Doppler velocity broadening estimates are given in Fig. 11a and the NUBF correction uncertainty estimates are given in Fig. 11b. The error in the decomposition the observed Doppler velocity to vertical motion and particle sedimentation is estimated to 2.0 $ms^{-1}$. The main concern in using spaceborne Ku-band radars for Doppler velocity measurements in deep convection is the sampling bias introduced by the relatively large radar footprint.

## 6. RECOMMENDATIONS

CubeSats and SmallSats have the potential to revolutionize Earth Observations from space. They significantly shorten the time period needed from concept to launch (RainCube took under 4 years from a paper study to launch from the ISS, compare to over 20 years for the JAXA/ESA EarthCARE Explorer mission). They have lower cost and can be easily stove in launchers of opportunity, thus, reduce several of the economical and “political” barriers that a community needs to overcome in order to have a successful proposal and mission.

In the context of deep convection, CubeSats/SmallSats can provide global, temporally resolved observations of clouds and precipitation processes using constellations on different time schedules, thus capturing the diurnal cycle of convection and different phases of the lifecycle of convective clouds (see section 4.1). The analysis shown in section 5 illustrates several areas where additional research is required in defining the measurement requirements for CubeSats and associated science objectives. In section 5, it was highlighted that recent technological advantages can permit Doppler measurements from Mini- and Small-Sats. However, the radar/radiometer footprint remaining fairly large and additional research is needed to quantify the sampling bias induced by the large footprint and to explore mitigation strategies.

There are several research areas that we could focus in the near future:

1. Quantify the sampling bias of the large footprint (especially for CubeSats) on convective motion and Path Integrated Attenuation (PIA) estimation. Conduct research on mitigation strategies using along- and cross-track oversampling along with deconvolution and reconstruction techniques (Schutgens and Donovan, 2004; Long and Brodzik, 2016). This work should be extended to DPCA approaches in SmallSats and MicroSats.
2. What is the optimum temporal/spatial sampling for a CubeSat constellation that aims to study the updraft mass flux of a deep convective cloud system?
3. Quantify the performance of D-train type of approach in estimating the updraft mass flux in deep convection using a constellation of CubeSats.
4. Radar and radiometer synergy in CubeSats for convective motion and precipitation estimation: what is the added value of combining a RainCube-like radar with a TEMPEST-D radiometer (see Fig. 21)? This is particularly relevant for future SCOUTS opportunities.
5. Explore the integration of CubeSat observations with existing Program of Record (POR) datasets (polar-orbiting radiometers, GOES-16) in order to improve understanding the lifecycle of convective clouds.
6. Extend the application of CubeSats at higher frequencies (W/G-band?). NASA-JPL is currently working in this direction.

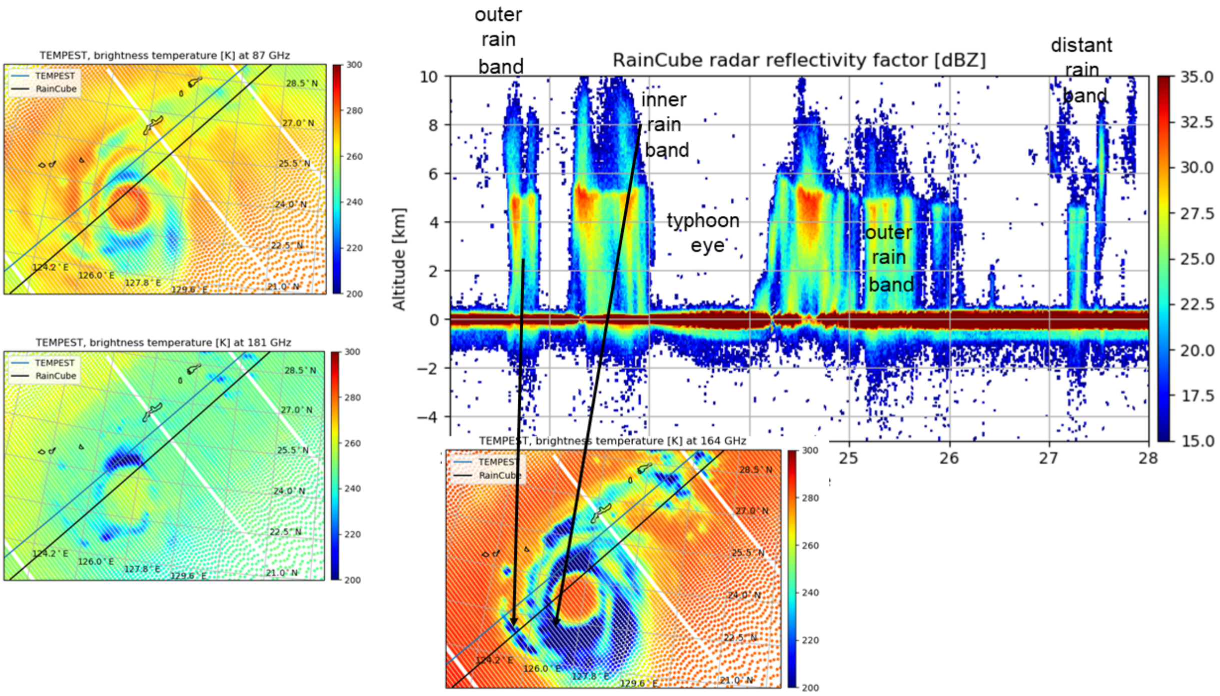



**Figure 21. Example of combined RainCube-TempestD observations for the asymmetric structure of Typhoon Trami.**

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